Modelling ship strike risk to fin, humpback and killer whales in British Columbia, Canada

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ABSTRACT

Many cetacean species are susceptible to mortality or serious injury from vessel collisions. Spatially explicit assessments of risk per whale can help identify potential problem areas to guide appropriate mitigation measures. Canada's Pacific waters host high cetacean densities and intense maritime traffic, and the issue of vessel collisions has taken on a high priority in British Columbia (BC) recently due to several major industrial development applications. Spatially-explicit statistical modelling and Geographic Information System (GIS) visualisation techniques identified areas of overlap between shipping activity and waters used by humpback, fin and killer whales. Areas of highest risk were far removed from areas with highest concentrations of people, suggesting that many beach-cast carcasses could go undetected. With few exceptions, high-risk areas were found in geographic bottlenecks, such as narrow straits and passageways. Port expansion and a proposed pipeline for carrying oil from Alberta to BC's north coast (with associated oil tanker traffic) would increase ship strike risk for all three species. The risk assessments illustrate where ship strikes are most likely to occur, but cannot estimate how many strikes occur. Propeller wounds on live killer whales are relatively common in the region, and fatal collisions have been reported in BC for all three species. Procedures were used to estimate potential mortality limits in accordance with a wide range of quantitative management objectives from jurisdictions around the world. While the extent of under-reporting of ship strikes has not been evaluated, the few known cases of collisions involving fin whales suggest that mortality due to ship strike for this species may already be approaching or even exceeding mortality limits under the most risk-averse management objectives. It is hoped that these risk maps may inform environmental impact assessments of marine traffic because it will be easier to plan new shipping lanes so that they avoid high-density areas for whales than it will be to move the lanes after they become entrenched.

KEYWORDS: SHIP STRIKE; CONSERVATION; SPATIAL MODELLING; REGULATIONS; ABUNDANCE ESTIMATE; MANAGEMENT OBJECTIVES; RISK ASSESSMENT; NORTHERN HEMISPHERE; FIN WHALE; HUMPBACK WHALE: KILLER WHALE

INTRODUCTION

Collisions with vessels cause serious injury and mortality in many cetacean species. Quantifying the population-level extent of ship strike mortality, however, is notoriously difficult; collisions are frequently unnoticed, and consequently go unreported (Laist *et al*., 2001; Panigada *et al*., 2007; Vanderlaan and Taggart, 2007). Ship strikes can jeopardise the viability of small populations (Fujiwara and Caswell, 2001), and the importance of the topic is reflected in its appearance in the terms of reference of both the Scientific and Conservation Committees of the International Whaling Commission (IWC).

Important areas for research include developing methods for quantifying ship strike mortality, assessment of the effects of such mortality at the population level and the development of appropriate mitigation measures. A valuable exercise to inform the estimation of the potential size of the problem and the identification of mitigation measures, involves spatially explicit risk assessment. Underlying this premise is a common-sense view that minimising spatial overlap between ships and whales is the best way to minimise ship strike risk. Although spatial overlap between ships and whales is not equivalent to collision risk, spatial overlap is obviously a prerequisite for ship strikes.

Canada's Pacific waters host high densities of cetaceans (Williams and Thomas, 2007) as well as intense maritime traffic (O'Hara and Morgan, 2006), but there has been little effort towards estimating cetacean mortality due to ship strikes. There is reason to believe that in British Columbia (BC) this issue has taken on greater urgency in recent years as considerable industrial development is occurring throughout coastal BC, including *inter alia*: major port expansions for Prince Rupert and Delta superport; a planned pipeline terminal for accepting condensate and dispensing crude oil to and from the Alberta tarsands oil fields, with associated petroleum tanker traffic; and potential offshore oil and gas exploration and production in Hecate Strait and Queen Charlotte Sound (Fig. 1). All of these developments would result in a considerable increase in shipping traffic and consequently an increase in the risk of whales being struck. Within Canada, there is a growing recognition of the need to assess the extent of cetacean mortality associated with human activities and to mitigate impacts where feasible. Canada has not specified a uniform set of quantitative management objectives to protect marine mammal stocks from anthropogenic mortality, but methods that take into account uncertainty in population vital rates and abundance estimates have been proposed to estimate potential limits to anthropogenic mortality of Canadian marine mammal stocks (Johnston *et al*., 2000; Williams *et al*., 2008). It is unclear what level of ship strike mortality would constitute a sufficiently large fraction of a cetacean population to warrant legislative management action in Canada.

Risk assessment is needed especially for humpback (*Megaptera novaeangliae*) and fin whales (*Balaenoptera physalus*), and for the small killer whale (*Orcinus orca*) populations found in the region. Commercial whaling in British Columbia (BC) brought baleen whale populations

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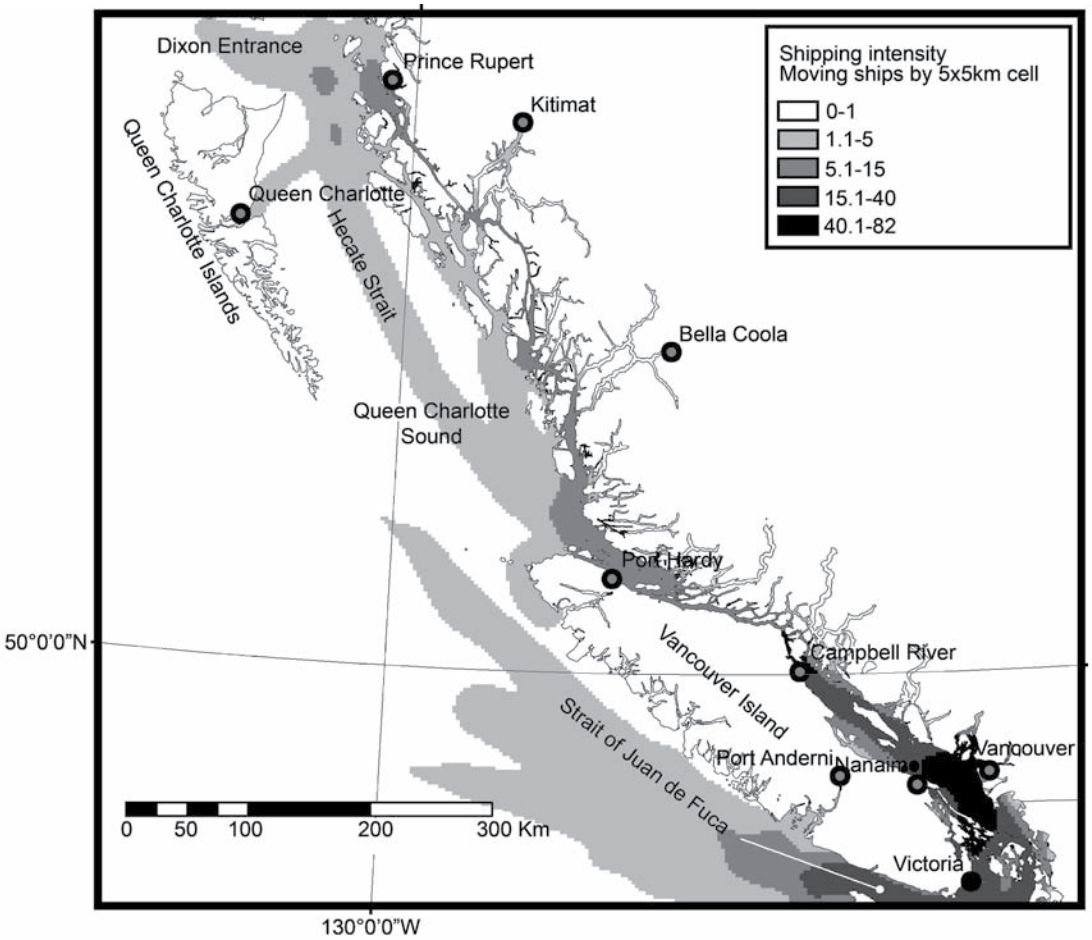

Fig. 1. Marine traffic vessel intensity (number of movements per grid cell) along the coast of BC for June, July and August, 2003.

well below historic levels of abundance (Government of Canada, 2006). In Canadian regulatory frameworks, ship strikes have been identified as important factors in the humpback, blue (*B. musculus*), fin and sei (*B. borealis*) whale recovery plans (Government of Canada, 2006), and for both resident and transient ecotypes of killer whales (Fisheries and Oceans Canada, 2007; 2008). Humpback, gray (*Eschrichtius robustus*) and fin whales have occasionally been reported to be struck by ships transiting the 'Inside Passage' (Douglas *et al*., 2008), which refers to the series of inland and protected waterways used by ships transiting between Johnstone Strait (northern Vancouver Island) and Prince Rupert (Fig. 1).

In this paper, results from a spatially-explicit risk assessment that identifies areas of overlap between whales and shipping activity in BC coastal waters are reported. This assessment is based on data from a recent systematic survey of Inside Passage waters of BC that yielded estimates of distribution and abundance for six cetacean species (Williams and Thomas, 2007). The assessment also includes shipping activity based on compiled and summarised information made available by the Canadian Coast Guard (CCG) that tracks ship movements through their Exclusive Economic Zone (O'Hara and Morgan, 2006). A secondary goal was to use existing abundance estimates to assess potential mortality limits for three cetacean species. Finally, the frequency of vessel collisions and propeller strikes are reported (based on scars seen in photographs of living animals) that have been reported in the region in the primary and grey literature. This minimum estimate of known vessel collisions is used to assess, qualitatively, the plausibility that ship strikes could be causing mortality that exceeds potential mortality limits calculated for BC waters according to procedures that have been used in other regions.

METHODS

Whale abundance and density surface fitting

Whale distribution data

Whale data used in the analyses were collected from a systematic line transect survey designed (Thomas *et al*., 2007) and conducted (Williams and Thomas, 2007) in BC coastal waters in the summers (June-August) of 2004 and 2005. The survey was conducted using 20m boats and covered coastal waters (out to approximately 80 n.miles) between the BC-Washington and BC-Alaska borders. Methodology and conventional distance sampling abundance estimates have been reported previously for several cetacean species from these surveys (Williams and Thomas, 2007; 2009). Additional data were also collected in August 2006, but funding limitations only allowed about half of the planned tracklines to be surveyed. As a result, potential mortality limits were estimated using the analytic abundance and variance estimates previously reported from the design-unbiased survey, i.e. data collected during the 2004 and 2005 field seasons (Williams and Thomas, 2007). However, data collected in 2006 were included in model-based, density surface fitting models (see below) for distribution maps to inform the risk analyses, in order to benefit from increased numbers of sightings for fitting the

density surface model. For the case of northern resident killer whales, in which every individual is known from annual censuses conducted by Fisheries and Oceans Canada (Ford *et al*., 2000), known abundance with zero variance was used to estimate mortality limits rather than using abundance estimates from the survey data; although the conventional distance sampling abundance estimates agree well with the known population size (Williams and Thomas, 2009). For humpback and fin whales, abundance refers to the average number of whales in the study area at the time of the surveys, rather than biological population size, because the fraction of the stock(s) using BC waters in summer is unknown.

Whale density surface fitting

Animal density was modelled using the density surface modelling engine in *Distance 6.0 Beta 5* (Thomas *et al*., 2006) following the four-stage approach outlined by Thomas *et al.* (2006): (1) fitting a detection function; (2) estimating whale abundance in each segment as a function of spatial covariates; (3) using the descriptive model to predict whale density throughout the study region; and (4) producing variance estimates. Candidate forms for the detection function were the hazard-rate and half-normal models (Buckland *et al*., 2001). Model selection was guided by Akaike's Information Criterion (AIC) and goodness of fit statistics. Trackline detection probability was assumed to be certain (i.e. $g(0)$ was assumed to be 1). The log of school size, $\ln(s)$, was regressed on the estimated detection probability at the perpendicular distance for each school. The predicted value of $\ln(s)$ at zero distance (where detection probability was assumed to be 1) was then back-transformed to provide the required estimate.

Effort and sightings data were modelled using the 'count' method (Hedley *et al*., 1999; Williams *et al*., 2006), which has been packaged into the Density Surface Modelling (DSM) engine in *Distance* (Thomas *et al*., 2006). Tracklines were divided into segments approximately 1 n.mile in length. Depth of the midpoint of the segment was estimated by overlaying the tracklines on a bathymetry grid in *ArcView 3.2*. The saturated DSM model was of the general form:

$$N \sim s(longitude, latitude) + s(depth) - offset$$

The DSM engine in *Distance* models abundance of whales in each segment using generalised additive models, using thin-plate regression splines (s) by calling the mgcv package in programme *R* (Wood, 2006). This saturated model was used unless a term was not significant at $p<0.05$, or if AIC favoured replacing the bivariate locational spline ($s_{\text{longitude, latitude}}$) with two one-dimensional smooths.

A gridded dataset was created, containing a value in every grid cell for each explanatory variable in the model. A square grid size of 2 n.miles on a side (i.e. 4 n.miles^2) was chosen for prediction. Values for the explanatory variables (latitude, longitude and depth) were calculated using the value at the midpoint of each grid square. The prediction grid data were passed to the selected model for each species in *Distance*, which called the predict.gam function in mgcv. The output of the model was an estimate of the predicted number of whale schools in each grid cell, based on each cell's latitude, longitude, depth and area. Animal abundance was calculated by multiplying the predicted density in each cell by expected school size from the size-bias regression in the detection function modelling step (Buckland *et al*., 2001) and by the area of each cell, and taking the sum of all values in the grid. The prediction grid was defined by the same shapefile as that used for designing the original survey (Thomas *et al*., 2007), so the model prediction only interpolated density between tracklines and did not involve extrapolation beyond the survey region.

Shipping movement data

The Canadian and US Coast Guards monitor ship traffic using radio communication, radar detection and an Automatic Identification System (AIS). The only AIS data used for this study were collected by the US Coast Guard in the transboundary waters of the Strait of Juan de Fuca. The Canadian Coast Guard (CCG) documents ship position approximately every 4 minutes with ship-identification (registered name and Lloyd's registry number), flag-state (country of registry), ship-type and size. Included in this database are ships over 20m in length, and ships engaged in towing or pushing any vessel or object more than 20m (other than fishing gear) that had a combined length of more than 45m. The database does not include vessels towing or pushing inside a log-booming ground, pleasure yachts <30m, or fishing vessels <24m and 150 tonnes gross, which are not required to report to the CCG.

Shipping movement analyses were based on shipping information for the calendar year 2003 as provided by the CCG (Pacific Region). The first complete year of data archived by the CCG (Pacific Region) was 2003, and these data were assumed to be representative of ship movement patterns off the BC coast for all years considered in this study (2004-06). To minimise computer processing time for the analyses, observations were reduced to one uniquely identifiable ship observation per hour per cell in a grid of 5×5km cells using data manipulation procedures in *SAS* (Cary, North Carolina: *SAS v9.3*). Ship identification was based on vessel name, call-sign and Lloyd's registry number. Shipping data were removed when ship movement between cells was not indicated (i.e. ensuring that data were from moving ships only). Finally, for each grid cell, data were summarised by calculating total number of uniquely identifiable ship observations ('Proc Tabulate': *SAS v9.3*), and these totals were used as an index of ship intensity throughout our study area (Fig. 1). This index of ship intensity is a minimum estimate of actual ship movements because a number of ships were not clearly identified in the dataset (i.e. ships tracked by radar were not always identified), and in regions where radar was not available some ships passing through Canadian waters were not tracked because they were not always required to call in (i.e. they were not destined for a Canadian port).

Mapping relative ship strike risk

A ship strike risk layer was created by multiplying the predicted whale density estimates at each grid point with the nearest value of shipping intensity. The resulting surface layers were explored for potential hotspots of elevated risk of ship strike for all three species of whales studied. These surfaces were created to quantify risk spatially, in relative terms within species, and no attempt was made to compare vulnerability to ship strike across species.

Shipping movement patterns, predicted whale density estimates, and relative ship-strike grids were mapped using Inverse Distance Weighting (IDW) ArcGIS v9.3 (ESRI 2002), which is an interpolation technique that estimates focal cell or point values by averaging values for neighbouring cells or points. Average values were calculated using a fixed minimum number of neighbour-values and variable radius. The effect of distance of neighbour cell on the estimated average value of the focal cell is affected by

distance of the neighbouring cell from the focal cell. Categories of gray-shading in the mapping were defined using 'Natural Breaks' or 'Jenks' method in ArcGIS 9.3.

Potential mortality limits

Canada does not use a generic set of quantitative objectives to calculate allowable annual anthropogenic mortality to marine mammal stocks. Consequently, a range of conservation objectives were considered that have been specified in various national and international frameworks (Wade *et al*., 2008; Williams *et al*., 2008). As an illustrative example, the Potential Biological Removal (PBR) calculations under the US Marine Mammal Protection Act were conducted using the default guidelines for assessing marine mammal stocks in US waters (Wade and Angliss, 1997), and are described as follows:

$$PBR = N_{min} x 0.5(R_{max}) x F$$

Where R_{max} is defined as the maximum theoretical or estimated net productivity rate (default value for cetaceans=0.04), F as the recovery factor, set to 0.5 for these stocks as recommended for depleted stocks and N_{min} as the 20[th] percentile of a log-normal distribution surrounding an abundance estimate:

$$N_{min} = N / e^{(0.842 x (\ln(1+CV(N)^2))^{1/2})}$$

where, N is the abundance estimate and $CV(N)$ is the coefficient of variation of the abundance estimate.

This first step toward estimating potential mortality limits is tentative because information is lacking for fin and humpback whales on stock definition and stock boundaries, and because this study lacks information for all three species on the proportion of the stock found in the study area in summer months. Applying mortality limits such as those estimated by PBR to a small area (more specifically to the average number of animals within an area), rather than to a biological population is a conservative approach. Lack of information on seasonal patterns in distribution and abundance is a weakness that will affect the estimates of risk (i.e. exposure to ships), but this is a precautionary first step and is the best that can be done with the existing information.

A review of US and Canadian status reports and grey literature was conducted to produce minimum estimates of known cases of ship strike and propeller wounds. Note that current mortality data are presented from scattered records reported throughout the year, but abundance, mortality limits, distribution and risk analyses are restricted to a summer, three-month period. Despite this temporal mismatch, there is no information available on seasonal variability in abundance of these species in the region. Consequently, the methods use all available information and, by including information on known mortality events from outside the summer season, err on the side of being precautionary.

RESULTS

Whale abundance and density surface fitting

Whale distribution, abundance and potential mortality limits

Previously reported abundance estimates for fin and killer whales suffered due to a lack of sightings (Williams and Thomas, 2007; 2009). Including the effort and sightings data from 2006 improved the fit of the detection function for both fin and killer whales. Although model-based abundance estimates that incorporated the additional data collected in 2006 had little effect on the point estimates of abundance for any of the three species, analytic abundance and variance estimates were used for estimating potential mortality limits due to known problems with reliability of variance estimates from model-based abundance estimators (Hedley *et al*., 1999; Williams *et al*., 2006). Abundance estimates and associated CVs used in the analyses are shown in Table 1. A comparison of six assessments of potential limits to annual anthropogenic mortality of fin, humpback and northern resident killer whales are presented in Table 1.

The highest density regions predicted for fin whales (Fig. 2) were found in Dixon Entrance and off the southern end of Queen Charlotte Islands. Fin whale density in mainland inlets was generally low, with one exception on the central coast. The highest-density regions for humpback whales were qualitatively similar to those of fin whales (Dixon Entrance and off the southern end of Queen Charlotte Islands), but humpback whale density in mainland inlets was much higher than it was for fin whales. For northern resident killer whales, the highest density region was Johnstone Strait, however, additional high-density areas were found in central coast waters.

Table 1

A comparison of mortality limits estimated for three cetacean species using six conservation objectives used in international conservation and management frameworks (after Wade *et al*. 2008).

		Fin whale	Humpback whale	Killer whale
Abundance		496	1,313	235
% CV		45.8	27.5	0
N_{min} (20[th] percentile)		332.3	1,024.9	235
Conservation approach:	**Formula:**			
IWC Scientific Committee[1]	2% of N_{best}	9.9	26.3	4.7
ASCOBANS 'unacceptable'	1.7% of N_{best}	8.4	22.3	4
ASCOBANS 'precautionary'	1% of N_{best}	5	13.1	2.4
PBR 'no bias or uncertainty'	$1/2\ R_{max} * N_{min} * 1.0$	6.6	20.5	4.7
PBR 'robust'	$1/2\ R_{max} * N_{min} * 0.5$	3.3	10.2	2.4
New Zealand MALFIRM	$1/2\ R_{max} * N_{min} * 0.15$	1	3.1	0.7

[1]The IWC Scientific Committee cautions that bycatch levels >2% of the best abundance estimate are unacceptable, and that takes of 1% of N_{best} (i.e. the same criteria as those used by ASCOBANS) warrant close attention (IWC, 1996, p.89).

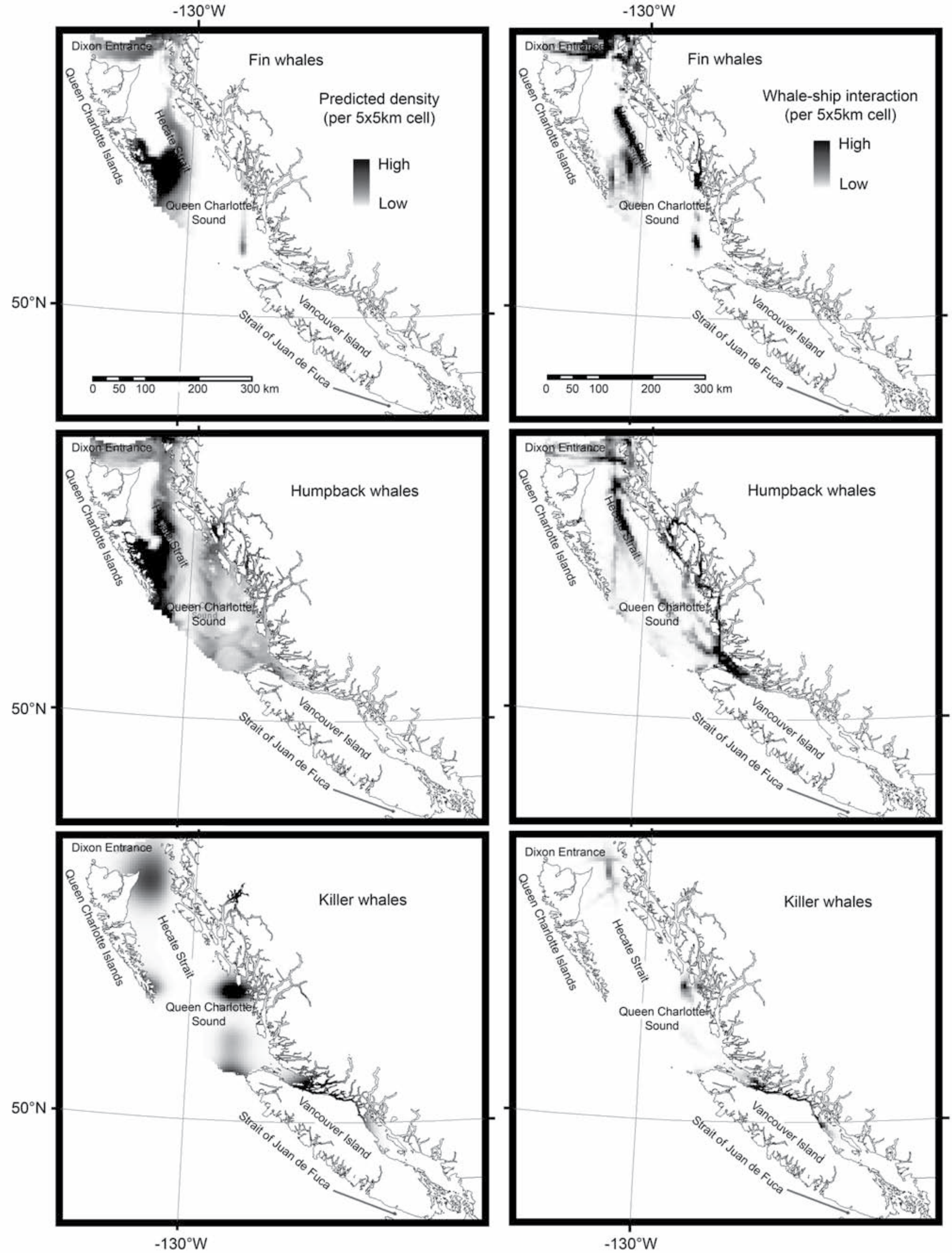

Fig. 2. Density surfaces for fin, humpback and northern resident killer whales (left-hand column), and intensity surfaces for whale-ship interactions (right-hand column) for fin, humpback and killer whales on the right (whale density x marine traffic vessel intensity: see Methods). Whale densities (numbers per grid cell) range from 0-5 for fin whales, 0-4 for humpback whales, and 0-1 for killer whales. Whale-ship interactions scale from 0-224 (fin whales), 0-841 (humpback whales), and 0-1,279 (killer whales).

Table 2

Known ship strikes affecting BC cetacean species, with summaries of events compiled from killer whale recovery strategies (Canada and the US), humpback and fin whale status reports (COSEWIC) (Douglas *et al*., 2008; Jensen and Silber, 2004), the newsletter of Vancouver Aquarium's BC Cetacean Sightings Network (*http://www.vanaqua.org*), and personal observations from Jackie Hildering (whalewatch naturalist working in Johnstone and Queen Charlotte Straits).

Year	Species	ID	Location	Fate of animal
1999	Fin whale	UNK	British Columbia (BC)	Fatal
2002	Fin whale	UNK	Puget Sound, Washington (WA)	Fatal
2002	Fin whale	UNK	Puget Sound, WA	Fatal
2002	Fin whale	UNK	Puget Sound, WA	Fatal
2002	Fin whale	UNK	Puget Sound, WA	Fatal
2004	Fin whale	UNK	West coast Vancouver Island (VI) BC	Fatal
2006	Fin whale	UNK	Northwest inland waters WA	Fatal
2006	Fin whale	UNK	Puget Sound, WA	Fatal
2004	Humpback whale	UNK	West coast WA	Fatal
2006	Humpback whale	UNK	Knight Inlet, BC	Uncertain
2006	Humpback whale	UNK	Swiftsure Bank (west coast VI, BC)	Uncertain
2006	Humpback whale	BCX0022 calf	Johnstone Strait, BC	Seen injured and disappeared
2006	Humpback whale	BCY0177	Johnstone Strait, BC	Serious injury
1995	Killer whale (NR)	UNK	British Columbia	Non-fatal injury
2005	Killer whale (NR)	A60	Johnstone Strait, BC	Non-fatal strike
2006	Killer whale (NR)	A82	Campbell River, BC	Injured and died following year
2006	Killer whale (NR)	C21	Prince Rupert, BC	Fatal
2006	Killer whale (NR)	A59	Campbell River, BC	Non-fatal strike (calf A82 injured)
2006	Killer whale (NR)	G39	Johnstone Strait, BC	Serious injury
2007	Killer whale (offshore)	UNK	Johnstone Strait, BC	Serious injury (dorsal cut off)
1998	Killer whale (SR)	UNK	Haro Strait, BC	Non-fatal strike
2006	Killer whale (SR)	L98	Nootka Sound (west coast VI, BC)	Fatal
2005	Killer whale (SR)	UNK	Haro Strait, BC	Non-fatal strike

Ship strike risk

Areas of relatively high risk of ship strikes for fin whales were found in Dixon Entrance (off northern Queen Charlotte Islands), and two areas coincidental with elevated shipping movement patterns in Hecate Strait, and at the entrance to one inlet system on the central coast (Fig. 2). Areas of relatively high risk of ship strikes for humpback whales were roughly similar to those for fin whales, but also occurred in Queen Charlotte Strait, Hecate Strait, and several inlet systems along the central coast. For killer whales, the region of highest ship strike risk was constrained to Johnstone Strait, where risk was estimated to be about an order of magnitude higher than anywhere else along the coast.

Minimum estimates of mortality and serious injury due to ship strikes

Evidence of injuries and mortalities due to vessel collisions is presented in Table 2. The number of cases reported for each species probably does not represent relative frequency of collisions, because killer whales are better studied in the region than the other two species. Similarly, much of the available information on collisions comes from Washington State, while the abundance estimates for assessing mortality limits apply only to BC waters.

DISCUSSION

This study presents an objective and quantitative framework for identifying areas of elevated risk of ship strike for whales based on existing data on whale distribution and shipping traffic intensity. A pattern emerges that is consistent among the three species of whales (humpback, fin and killer), whereby areas with the highest relative risk (i.e. risk of ship strike within species) are found in 'bottlenecks'; regions where whale and boat densities are both concentrated (Fig. 2). Ship strike risk to killer whales is highest in Johnstone Strait, and for humpback whales, the Queen Charlotte and Johnstone Straits (northeast of Vancouver Island) and the narrow passages of the central coast are relatively high-risk areas for both species. Although the waters off southern Queen Charlotte Islands host the highest densities of fin whales, risk of ship strike is relatively low because of the low levels of shipping traffic there; the highest relative risk areas are found in Dixon Entrance where ship traffic is more concentrated.

While the risk assessments can predict where ship strikes are most likely to occur, they cannot predict how many strikes are actually occurring. One technical development that will assist these ongoing efforts is a more consistent use of the AIS system coastwide. While AIS coverage in BC is currently sparse, the system is expected to come into widespread use in the near future. At that point, the risk metric could be recalculated in absolute, rather than relative units. Efforts will still stall, however, at the point of evaluating whether current mortality rates can be deemed acceptable. A considerable hurdle for setting mortality limits is the inability to state Canada's current management objectives in quantitative terms and whether quantitative objectives will be based on N_{best} or N_{min} (i.e. the degree of uncertainty that will be tolerated). In BC, this is especially problematic for fin whales because of the large uncertainty associated with existing abundance estimates (Williams and Thomas, 2007). For the two baleen whale species, limits for an area, rather than a population, have been calculated because it is currently unknown what fraction of the populations was likely to be in the study area at the time of the survey, which will differ among species. In a related way, ship strike mortality may apply to killer whales year-round in this region but only for a limited period for the other species. Until information on stock boundaries and seasonal patterns in abundance becomes available, the range of mortality limits presented are necessarily simplistic, but a useful starting point for discussion. Based on objectives from the different management approaches reviewed (Table 1), potential limits to anthropogenic mortality would vary by an order of magnitude for both fin and humpback whales (Table 1). Regardless of the management approach and objectives that Canada eventually specifies, mortality limits will be relatively low for these species, both because populations are small and uncertainty in abundance estimates is large (Table 1).

It remains to be seen whether ship strikes are causing mortality rates that exceed all but the most precautionary limits to anthropogenic mortality, but a cursory review of the primary and grey literature reveals that ship strikes are far more common in the region than expected.

Estimating ship-strike mortality

Fin whales

Many British Columbians first became aware of the threat that ship strikes pose to fin whales in June 1999, when a cruise ship arrived in the port of Vancouver with a fin whale carcass draped over its bulbous bow. Although mortality rate estimates based on anecdotal information received through self-reporting and compiled in an informal monitoring scheme (Table 2; average of one animal per year in BC-Washington waters) are no doubt much lower than total mortality rates, estimated rates would still be high enough to trigger management action in other jurisdictions (e.g. New Zealand; Table 1). Nevertheless, high priority must be placed on identifying the degree to which under-reporting of ship strikes is occurring for this species. Existing abundance estimates for fin whales are accompanied by such large CVs (Williams and Thomas, 2007) that only the most catastrophic population declines problems would be detected. This lack of robust abundance estimates, coupled with an apparent propensity for fin whales to be struck by ships (Douglas *et al*., 2008; Laist *et al*., 2001), suggests that understanding ship-strike impacts on fin whales should be a priority for future work (Panigada *et al*., 2008).

Humpback whales

Collisions with humpback whales are reported frequently enough to raise concern. Three of the five reported collisions (Table 2) occurred in the 'high-risk area', which may reflect a true tendency for ship strikes to occur in areas where humpback whales aggregate and where shipping may intensify in narrow coastal passageways (i.e. 'bottlenecks'). Alternatively, it could reflect simply the high probability that whalewatchers, researchers and naturalists will detect and report such events because they too would be drawn to places where whales aggregate. One pattern seen in these sparse data is a tendency for humpback whale collisions to result in an uncertain fate of the animal. A priority is thus to ensure that additional resources are allocated to allow long-term monitoring of struck individual animals to assess post-strike survivorship. However, it is clear that under-reporting would have to be severe for annual mortality to be approaching anything but the most precautionary conservation objectives for this species. It is possible that 10-20 (Table 1) humpback whales could be killed each year by ships in BC and this level of mortality could go unnoticed or unreported, but existing data do not allow the plausibility of this scenario to be evaluated.

Killer whales

The number of collisions reported between resident killer whales and vessels was surprising given the attention paid in BC to whalewatching guidelines. However, resident killer whales are censused in most years by Fisheries and Oceans (DFO) Canada researchers (Ford *et al*., 2000) and heavily scrutinised by commercial whalewatchers, making it less likely that vessel strikes go unreported for killer whales than for fin or humpback whales. The small size and highly social nature of BC killer whale populations means that these populations are unable to absorb anything beyond very low levels of anthropogenic mortality (Table 1; Williams and Lusseau, 2006). Any limit to anthropogenic mortality established for these small populations would be low, regardless of the conservation approach (Table 1) and the minimum mortality or serious injury rates due to vessel collisions based on anecdotal information and self-reporting approach or exceed these limits already. Fortunately, BC killer whale populations are very well studied, and variation in mortality resulting from ship strikes would be detectable, provided that DFO's Cetacean Research Program and the Center for Whale Research (Washington State) have adequate resources to continue their long-term monitoring study of resident killer whales. However, clearly attributing a proportion of mortality to ship-strikes, or any anthropogenic cause, remains an obstacle for conservation efforts. For this reason, increasing the recovery and necropsy rates of killer whale carcasses is a priority for future research supporting the conservation of this species (Raverty and Gaydos, 2004).

Utility of the approach

The approach described here represents an early attempt to overlay whale and shipping density to calculate the spatial distribution of relative risk, which has been identified by the IWC Scientific Committee as an important step in understanding ship strikes. The approach adopted, namely to use GAM-based spatial models to estimate whale distribution (Hedley *et al*., 1999; Williams *et al*., 2006) and overlay spatially explicit data on marine vessel traffic intensity, provides a reasonable, quantitative and objective method to identify areas in which animals are particularly vulnerable to human activities. There is also value in reporting a range of mortality limits, when conservation objectives are not framed in easily quantifiable terms (Wade *et al*., 2008). For example, one of the motivations for this study was to assess the likely impacts on whales resulting from the expansion of the Port of Prince Rupert to accommodate increased bulk and container shipping. Given that most of the traffic is expected to travel in an east-west direction, this port development might lead to greater risk to fin whales than humpback or killer whales. On the other hand, fin, humpback and killer whales would all be impacted by the construction of a pipeline to Kitimat (Fig. 1) and the concomitant rise in petroleum tanker traffic in narrow passages along the central coast (Fig. 1: the coastal mainland north of Port Hardy and south of Prince Rupert). Given the difficulty in adequately monitoring oil pollution in most regions of BC, shipping intensity is one of the best available proxy indices for ship-source oil pollution (O'Hara and Morgan, 2006). In the same way, movement patterns for large vessels will probably also serve as a proxy for catastrophic oil spill risk. In August 2007, a barge loaded with a fuel truck and other equipment tipped over in the area identified to be the area of highest risk for interactions between killer whales and ships (Fig. 2). The accident spilled approximately 10,000L of diesel fuel and a similar volume of other hydrocarbons. It was estimated that approximately 25% of the northern resident killer whale population was seen in the vicinity of the spill and may have been exposed to fuel (Williams *et al*., 2009).

Quantitative risk assessments such as those presented here can be useful for identifying areas of overlap between intense or high-risk human activities and relatively large fractions of wildlife populations. This framework might be useful for evaluating various least-cost scenarios to plan new shipping routes that minimise threat to whales while also minimising disruption to industry. It would certainly be easier to consider whale distribution early in the planning stages before environmental impact assessments are completed, permits attained, business/operation plans are developed and infrastructure is built. There is a need for research to inform policy as soon as possible, before shipping traffic patterns become established, because once entrenched and integrated into business plans, shipping

routes become difficult to modify. For humpback and killer whales, several channels along the Inside Passage emerge from the analyses as candidates for places where ships might be requested to travel at low speed, or to avoid altogether where feasible. Future risk assessments along these lines can inform management of protected areas and lead to efficient resource allocation for emergency preparation and response measures. If there is an accident, the industry responsible for the accident will likely benefit from such emergency preparation as this will lead to a more efficient response.

As Canadian management objectives for marine mammal stocks are being developed and articulated in quantitative terms (Hammill and Stenson, 2007; Johnston *et al*., 2000; Williams *et al*., 2008), it is time to assess the population-level consequences of ship strikes and non-fishery mortality in similarly quantitative terms. Fisheries and Oceans Canada is developing a regional marine mammal response network to respond to cetacean strandings, particularly for those species that are listed under Canada's Species at Risk Act. The spatial statistical modelling methods presented here provide a useful, visual tool for managers to identify potential problem areas, to manage shipping activities accordingly in as efficient a manner as possible, to allocate funds in priority regions for research, for identifying priority beaches to monitor for carcass detection and possible recovery and to mitigate impacts wherever possible.

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